SENSOR FORMULATION FOR THE DETECTION OF GAS COMPOSITON AND METHOD OF MAKING SAME

BACKGROUND OF THE INVENTION

5   Microorganisms pervade our environment affecting our lives in both beneficial and

harmful ways. For this reason there is an ever increasing requirement to provide a sensitive,

effective, speedy mechanism for the detection, identification and study of the presence and

metabolic activity of microorganisms.

10   In recent years the science of microbiology has experienced considerable advancements.

This is particularly true for the field of sensors used in the detection, identification and analysis

of the behavior of microorganisms. While progress has been made in the field of monitoring

microorganisms, inefficiencies in the commonly used monitoring methods still exist. For

example, a slow but effective procedure for antimicrobic susceptibility testing, the Bauer-Kirby

15   Disc Method, is still used in hospital environments. This method uses the presence or absence of

visible growth of the microorganisms to indicate the efficacy of an antimicrobic compound, and

generally requires an 18 to 24 hour incubation period to allow for microorganism growth before

a result can be obtained.

        Another popular method for antimicrobic susceptibility testing is the broth micro-dilution

20   method, such as the Sceptor RTM. System for identification and antimicrobic susceptibility

testing of organisms (Becton Dickinson Diagnostic Instrumentation Systems, Sparks, Md.). That

system uses a disposable plastic panel having a plurality of low volume cupulas (ca. 0.4 ml per

cupula), each containing a different test compound or a different concentration of a test

compound dried on the cupula surface. The organism to be tested is suspended in the desired

25   testing medium, and aliquots are delivered to the individual cupulas of the test panel. The reagent

dried on the panel dissolves in the sample, and the system is then incubated overnight (18 to 24

hrs.) to allow sufficient time for the organisms to interact with the reagent and for visible growth to appear. The panel is subsequently examined visually for the presence or absence of growth, thereby obtaining information on the susceptibility of the organism undergoing testing. Additional wells aid in identifying the organism. However, this test method, like the Bauer-Kirby Disc Method, suffers from the drawback of also requiring a long incubation period.

In recent years efforts have been made to avoid the long incubation times required for the above discussed monitoring methods. These innovations have focused on the monitoring of metabolic activity of microorganisms rather than monitoring the growth of colonies. Many approaches to monitoring metabolic activity of microorganisms have been reported in the attempt to rapidly and accurately monitor such metabolic activity.

One innovation in the field of microorganism monitoring is an apparatus, which utilizes light scattering optical means to determine susceptibility by probing the change in size or number of microorganisms in the presence of various antimicrobic compounds. An example of commercial instruments, which utilize this methodology is embodied by the Vitec System (BioMerieux Corp.). At best this system is expected to yield information on antimicrobic susceptibility of microorganisms within 6 hours for many organism and drug combinations. Other combinations can require as long as 18 hours before the antimicrobic susceptibility of the organism can be determined by the Vitech System method.

In an effort to improve on the Bauer-Kirby procedure, modifications have been developed which allow certain samples to be read in four to six hours. However, this modified system is destructive in nature, requiring the spraying of a developing solution of a color forming dye onto the test plate. The destructive effect of the developing solution prohibits re-incubation

and reading at a later time if the initial rapid technique fails. Thus, the experiment cannot be continued for a standard evaluation at a later time.

Still other approaches have involved monitoring of microbial oxygen consumption by the measurement of pH and/or hemoglobin color change, or by the use of dyes such as triphenyl-

5   tetrazolium chloride and resazurin, that change color in response to the total redox potential of the liquid test medium.

The monitoring of the consumption of dissolved oxygen by microorganisms, as a marker of their metabolism, has been studied for many years. For example, C. E. Clifton monitored the oxygen consumption of microorganisms over a period of several days using a Warburg flask in

10.   1937. This method measured the change in oxygen concentration in a slow and cumbersome manner.

The "Clark" electrode, an electrochemical device, is also commonly used to measure dissolved oxygen. Unfortunately, the Clark electrode consumes oxygen during use (thereby reducing the oxygen available to the microorganisms) and the "standard" size electrode is

15   typically used only to measure volumes of 100 mls or greater to prevent the electrode from interfering with the measurements.

A "miniature" Clark electrode has been described, but this electrode is a complicated multi-component part, which, like the larger electrode, must be in contact with the solution being measured. While an oxygen permeable membrane can be used to prevent the electrode

20   components of the device from interacting with the constituents of the test solution, the oxygen must still equilibrate between the test solution and the measurement system and is consumed once it passes the membrane.

Optical systems which can yield oxygen concentration data, have been developed to overcome the shortcomings of the Clark electrode systems. The main advantage of such optical methods is that the instrumentation required to determine quantitative value does not itself make physical contact with the test solution. Optical techniques allowing both colorimetric and fluorometric analyses for oxygen to be carried out rapidly and reproducibly are known, and costs for such analyses are often quite low. For example, several luminescent techniques for the determination of oxygen have been described which are based on the ability of oxygen to quench the fluorescence or phosphorescence emissions of a variety of compounds. However, such methods have not been readily adapted to microbial monitoring. Further, such systems, like the Clarke Electrode system are limited to monitoring only the consumption of dissolved oxygen by microorganisms.

Other systems have been described that provide information on the presence, identity and antimicrobic susceptibility of microorganisms in a period of eight hours or less. Wilkins and Stones in U.S. Patent No. 4,200,493 disclose a system that uses electrodes and a high impedance potentiometer to determine the presence of microorganisms. In U.S. Patent No. 3,907,646 Wilkins et al disclose an analytical method which utilizes the pressure changes in the headspace over a flask associated with microbial growth for the detection and surveillance of the organisms. U.S. Patent No. 4,220,715 to Ahnell, discloses a system wherein the head space gas above a test sample is passed through an external oxygen detector for determination of the presence of microorganisms. Ahnell, in U.S. Patent No. 4,152,213, discloses a system for analysis by monitoring the vacuum produced by growing organisms in a closed head space above a test sample. U.S. Patent No. 4,116,775 to Charles et. al is an example of the use of optical means based on the increase in turbidity or optical density of a growing microbial culture for the

detection and monitoring of bacterial growth. As with the Clarke Electrode systems, these systems are designed to provide data limited to oxygen consumption.

U.S. Patent 5,629,533 issued to Ackley et al. is exemplary of optical sensors, which have been developed for monitoring carbon dioxide levels on a continuous basis. Such sensors involve the use of glass fiber optics in combination with a sol-gel sensor element, which contains a chemical indicator sensitive to the presence of carbon dioxide. This system encompasses a grooved substrate with a sol-gel material having a chemical indicator adhered within the grooves. Fiber optic cables are coupled to the grooves and as light is passed through the fiber optic cables, the transmission is affected by the sol-gel sensor element.

While testing methods as exemplified above have improved in recent years to provide faster more accurate means of detecting the growth and metabolic activity of microorganisms, it is a common shortcoming of such testing methods that none of the innovations have provided a biological sensor that is capable of simultaneously detecting growth of both anerobic and aerobic microorganisms in a sample. This limitation in commonly used monitoring systems exists because such systems typically allow only one gas component to be detected in one sensor unit.

Gas composition monitoring systems, which can be used to detect metabolic activity of microorganisms are limited to monitoring either oxygen or carbon dioxide. Carbon dioxide sensors can use an acid-base indicator chromophore to modulate the signal output of a fluorophore. In such a system the chromophore absorbance spectrum changes when the pH value of a measured sample changes. The system is able to determine the carbon dioxide level because the pH value of a measured sample depends upon the carbon dioxide level of the sample environment. A monitoring system, which determines metabolic activity of microorgansims by employing an oxygen sensor, can employ an oxygen sensitive fluorophore to detect the oxygen

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level changes in a sample environment. Prior to the present invention, the combination of the ability to monitor both carbon dioxide and oxygen levels in a gas composition simultaneously was frustrated by the overwhelming problem of cross-talk between the system sensors.

The present invention addresses this problem by providing a sensor formulation and system that can respond independently and simultaneously to oxygen and carbon dioxide.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide an improved monitoring system to detect the presence of, and to evaluate the metabolic activity of anerobic or aerobic microorganisms present in a liquid or semi-solid media. It is another object of this invention to provide a microbial monitoring system which can independently and simultaneously monitor oxygen levels and carbon dioxide levels in a gas composition. It is another object of the present invention to provide an improved system that can detect and/or monitor the activity of oxygen consuming enzymes or enzyme systems as well as the effect of growth inhibiting compounds, such as antibiotics on microorganisms. It is another object of the invention to provide a novel formulation for use in monitoring metabolic activity of an organism. It is another object of the invention to provide a means for minimizing the cross-talk between distinct gas component sensors, which are simultaneously monitoring different components of a gas composition. It is another object of the present invention to provide a method of making an improved formulation, which can be used to monitor the metabolic activity of a microorganism by individually and simultaneously detecting levels of oxygen and carbon dioxide in a gas composition. Additionally, it is an object of the present invention to provide a method for monitoring

metabolic activity of a microorganism, the method encompassing the use of the monitoring system of the present invention.

The above and related objects are realized by the present invention. The present invention includes the use of a novel fluorescence detection system wherein fluorescing sensor compounds are employed to measurably respond individually and simultaneously to the level of oxygen and the level of carbon dioxide associated with the metabolic activity of a microorganism with minimal or no cross-talk between the different sensor compounds.

The fluorescence system of the present invention can be employed with a modified commercially available fluorescence reading device, such as, but not limited to a breadboard configured from a BD 9050 instrument. The modified florescence reading device can be so modified as to have at least two sensors, each sensor being separately matched to the wavelength of a corresponding fluorophore dye. An example of such a modified fluorescence reading instrument can be the commercially available BD 9050 device that has been modified to have two sensors matched to the respective wavelengths (sensitivity) of two corresponding fluorophore dyes; one of the fluorophore dyes being included in the formulation of the present invention for the purpose of reacting to oxygen levels in the sample being studied and the second fluorophore dye being included in the formulation for the purpose of reacting to the carbon dioxide levels of the sample being tested. It is within the concept of the present invention that, if it is desired to measure additional gases in a gas composition, additional distinct fluorophore dyes corresponding to additional sensors for the additional gases to be monitored can be employed. The additional sensors can be separately and distinctly matched to the respective wavelengths of the additional corresponding fluorophore dyes as necessary.

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The sensor formulation of the present invention can be brought into contact with the test sample (either directly or separated by an oxygen permeable membrane) and the level of fluorescence for each of the fluorophore dyes of the composition can be measured using fluorescence reading equipment as described above. An increase in fluorescence is indicative of

5 respiring aerobic microorganisms, which utilize (and thereby reduce) the oxygen in the sample.

The system can, thus, be used to detect a variety of respiring microorganisms, both anerobic and aerobic. It is further anticipated that this system can be used to detect the effectiveness of compounds such as antibiotics on the metabolic activity of microorganisms.

10 BRIEF DESCRIPTION OF THE FIGURES

FIG 1 shows the spectra of the sensor formulation of example 4 at 570nm. Sensor responses under N_2 and CO_2, CO_2 and air, air alone, and N_2 alone are graphically displayed.

15 FIG 2 shows the spectra of the sensor formulation of example 4 at 470nm. Sensor responses under N_2 and CO_2, CO_2 and air, air alone, and N_2 alone are graphically displayed.

DETAILED DESCRIPTION OF INVENTION

The biological sensor system of the present invention provides a novel sensor formulation

20 which when employed in the sensor system is capable of detecting the growth of both anaerobic and aerobic microorganisms in a sample. The unexpected result of simultaneously sensing changes in oxygen and carbon dioxide gas levels in a gas composition with minimal to no cross talk between the distinct sensors for the two gases is achieved due to the novel sensor

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formulation. The sensor formulation is composed of a mixture of chromophore, fluorophores, and supporting inert materials in such a way that each active fluorophore dye can respond to a specific gas composition change in a distinct manner without cross-interaction with the simultaneous composition changes detected by another fluorophore dye in the same sensor matrix. The sensor system of the present invention achieves this minimization of cross-talk between sensors by employment of the novel sensor composition.

The present invention, therefore, provides a novel formulation of composition for a "combi-sensor" for CO_2 and O_2 detection-in one sensing element; the method of manufacturing the sensor; and the use of the sensor to detect the growth (or the inhibition of growth as may be the case with anti-biotic drugs) of a large variety of disease causing microorganisms by both CO_2 production and O_2 consumption. It is also possible to use this sensor to detect the growth (or the inhibition of growth) in eukariotic cells, such as those grown in tissue culture and used for drug screening.

The novel formulation of the present invention allows both CO_2 production and O_2 consumption to be monitored without the expected cross-talk between sensors. Thus, as the CO_2 level of the sample changes the chromophore absorbance spectrum changes. The CO_2 sensor employs an acid-base indicator chromophore as a modulator to modulate the signal output of a fluorophore dye. As the CO_2 level of the sample environment changes, the pH value correspondingly changes. The chromophore absorbance spectrum changes in relation to the change in pH value. The O_2 sensor employs an oxygen sensitive fluorophore dye that correspondingly changes with a change in O_2 levels in the sample environment. The sensors in a fluoroscence reading device can be tuned to the wavelength of distinct dyes for each of the

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separate gases being monitored; however, the cross-talk between the different sensors can be so severe as to nullify any effort to monitor the gas composition.

The present invention solves this problem of cross-talk between sensors and provides distinct sensors giving high returns for each of the monitored gases by use of the novel sensor formulation. By way of example of the present invention, any O_2 sensitive fluorophore dye can be coated on to a heavier density silica powder. The dense silica powder causes the fluorophore coated silica to settle to the bottom of the sensor matrix as it is formed. The fluorophore dye which is used for CO_2 detection is coated on a lighter density silica, which results in the CO_2 associated fluorophore being floated throughout the sensor matrix. The acid-base indicator chromophore is made into an emulsion into the sensor matrix and therefore dispersed throughout the sensor matrix. By careful selection of the formulation components, the spectra profile of the O_2 sensitive fluorophore and CO_2 sensitive fluorophore can have minimum or no overlaps. The O_2 signal operates near independently from the CO_2 variations due to the segregated configuration of the different sensors, which results from the distinct densities of the selected silica used during matrix formation. Similarly, the CO_2 modulation operates near independently from the oxygen level sensor due to the segregated configuration of the formulation described above.

EXAMPLES

The sensor formulation can be composed of a mixture of chromophore, fluorophores, and supporting inert materials A non limiting example of the novel sensor formulation of the present invention can include (a) tris(4,7-diphenyl-10-phenanthroline) ruthenium dichloride pentahydrate; (b) 1.1',3,3,3',3'-Hexamethylindodicarbobyanine iodide; (c) an acid-base indicator

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dye; (d) a silicon polymer; (e) a hydrogen-silicon compound; (f) a catalyst; and optionally (g) an inhibitor and a method for preparing the novel composition. Importantly, the selection of components of the novel formulation allows one of ordinary skill in the art to tailor the sensor system to provide a clear gas composition determination for each sample being tested. It is also

5 important to understand that while the examples provided are directed to a sensor formulation and system, which can simultaneously detect O_2 and CO_2 levels in a gas composition, the formulation and system can be, if desired, expanded to include additional sensors and additional corresponding fluorophore dyes which can enable the simultaneous monitoring of additional gases. The sensor system therefore has a very broad range of capabilities and is not limited to

10 the examples described herein.

Formulations for some non-limiting examples of the sensor composition of the present invention are provided in Table 1. The specific components shown for each of the examples of Table 1 are representative of components which can be selected to achieve the present invention. The novel formulation of the present invention can include any mixture of chromophore,

15 fluorophores, and supporting inert materials which in combination result in a high return of the fluorescent signal for the distinct fluorophore dyes with minimal to no cross talk between the corresponding sensors.

TABLE 1

Example No.	1	2	3	4
Components				
MCP Stock Sol.[1]		0.5g		
HFCS[2]	0.3g	0.41g	0.2g	0.2g
Cresol Red[3]				0.36g
BTB dye[4]	0.3g		0.3g	
TiO$_2$	0.03g	0.03g	0.3g	0.03g
Polymer Part A[5]	21.0g	21.0g	21.0g	21.0g
Polymer Part B[6]	3.5g	3.5g	3.5g	3.5g
RFCS[7]		0.26g	0.25g	0.25g
1% Ru/EtOH	0.2g			
Settling time	3 hr.	3 hr.	3 hr.	3 hr.
Time/Temp	overnight/90°C	Overnight/75°C	3.5 hr./75°C	3.5 hr./75°C

[1]MCP Stock Sol. is 0.19 g m - cresol purple + 4.54g CAPS + 0.086g thymolphtalein + 22.14 g 1N NaOH + 78.5g DI H$_2$O stock solution.

[2] HFCS is a HIDC Flurophore Coated Silica.

[3] Cresol Red Stock Sol. is 0.345g Cresol Red + 0.54g Tricine + 4.95g 1N NaOH + 0.19g KCl + 25.2g DI H$_2$O.

[4] BTB dye is 2.0g BTB + 28.0g CAPS + 0.53g thymolphthalein + 16.0g 1N NaOH + 0.65g KCl + 100g DI H$_2$O.

[5] Polymer Part A is a polydimethylsiloxane; preferably a vinyl dimethyl terminated polydimethylsiloxane.

[6] Polymer Part B is a mixture of polymethylhydrodimethyl siloxane copolymer and a siloxane copolymer.

[7] RFCS is Ruthinium Flurophore Coated Silica.

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A modified BD 9050 fluorescence reading device was provided with channel

configurations as shown in Table 2. Similar channel configurations can be provided for any

fluorescence reading device which one of ordinary skill in the art would use to monitor

metabolism of a microorganism

Table 2
Channel Configurations (modified BD 9050)

ID	Channel	EX Filter	EM Filter	LED current (mA)	Feedback Resis (R_1inM)
NB1314	A (O_2)	467IF10	660IF40	20	25
	B (CO_2)	573IF12	630IF40	20	10

To prepare a 1.1',3,3,3',3'-Hexamethylindodicarbocyanine iodide hereinafter called

"HIDC") coated silica, a solution of 0.0715g of HIDC in 40g of 95% ethanol was made. The

solution was then mixed with 54g of Degussa Aerosil® R812 Silica (hereinafter called "R812").

The mixture was then air dried and the resulting solid was grinded.

A Cresol Red Indicator stock solution (hereinafter called "CR") was prepared by

dissolving 0.345g of Cresol Red (CAS# 1733-12-6), 0.54g of Tricine (CAS#5704-04-1) and

0.19g of KCl in 4.95g of 1N NaOH and 25.2g of Deionized water.

A Tris(4,7-diphenyl-1, 10 phenanthroline Ruthenium Chloride Pentahydrate) Ruthenium

(II) Chloride Hydrate coated silica (hereinafter called "RFCS") was prepared according to the

method described in U.S. patent 5,567,598, the complete disclosure of which is fully

incorporated herein by reference.

A heat curable silicon base polymer was made by mixing a vinyl terminated

polydimethylsiloxane with various amounts of catalyst and inhibitor and a crosslinker, which is

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a polymethylhydrodimethysiloxane copolymer or a mixture of a vinyl terminated polydimethylsiloxane and a polymethylhydrodimethylsiloxane copolymer. The catalyst can be included in the formulation from 1ppm to 5 % and the inhibitor can be included from 1ppm to 10%. Non-limiting examples of satisfactory catalyst and inhibitors are platinum catalyst and cyclic vinylmethyl-dimethylsiloxane inhibitor as light reflectors.

The sensor formulation can consist of 0.36g of CR, 0.2g of HIDC coated silica, 0.03g of DuPont Ti-Pure Titanium Dioxide, and 21g of polymer. The resulting mixture can be mixed mechanically. RFCS (0.25g) can be added to the above mixture and mixed again. After the second mixing of the formulation, 3.5g of a crosslinker can be added and mixed the third time. Any suitable crosslinker can be employed depending upon the degree of cross-linking desired. Two grams of the resulting sensor mixture was loaded into a Bactec 9000 glass bottle. The sensor bottle can then be allowed to set at ambient room temperature for three hours followed by heat cure at 75° for 3.5 hours. Variations on this method can be made without departing from the concept of the present invention.

The combination sensor signals are measured by two separate detectors at two different wavelengths of a same instrument unit on a same sensor device. The breadboard used to monitor sensor function in the examples was made from a modified BD 9050 instrument. The instrument was modified so as to match the distinct wavelengths of the dyes/fluorophores in the sensor composition to the instrument. Two detector channels were provided in the modified instrument. One was provided for oxygen variation signals and the second was provided for CO_2 variation signals. The wavelength control of any detector can be accomplished by appropriate LED's or filters or the combination of the two. The simplicity of the modifications to any fluorescence reading capable instrument is within the ordinary skill of one familiar with such instruments.

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Approximately 30 ml of deionized water was added to the sensor formulation and the container was sealed with a butyl rubber septum. The initial signal of the sensor formulation was measured in the modified fluorescence reading device as signals under the category "Air". It was then flushed with nitrogen to obtain the signal measurement under "N_2" or oxygen-free

5   environment. The same sensor was then flushed with nitrogen contained 30% CO_2 for "30% CO_2/N_2 signals. Finally the same sensor was flushed with 30% CO_2 balanced with air and the corresponding signals were measured. FIG's 1 and 2 provide a graphic display of CO_2 monitoring of a test sample, example 4. Shown is the spectra of the sensor formulation of example 4 at 570nm and 470nm respectively. Sensor responses under N_2 and CO_2 , CO_2 and air,

10   air alone, and N_2 alone are graphically displayed. Table 2 provides the results of monitoring of examples 1-4 using the same technique described above. It can be seen how one of ordinary skill in the art can control the results of sample monitoring by varying the composition of the sensor formulation.

Signal measurements with a modified BD9050 device under various gas compositions are

15   summarized below with examples including a preferred embodiment, example 4.

The best result was obtained with example 4 which represents a high dynamic range and low cross-talk in both oxygen and carbon dioxide channels. The dynamic range measures the signal change upon gas composition changes. The cross-talk indicates the independency of one gas composition change from the other.

20   To provide consistency in evaluating the formulations of the present invention, the test material employed for all formulation examples was an artificially prepared gas composition. The prepared gas composition includes 30% CO_2 and is a generally accepted gas composition to mimic real microbiology growing profiles. The glass sensor bottle, which contains the artificial

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gas composition is capped with a rubber septum. A double-needle device is then inserted with one needle connected to a gas supplier and the other needle open to the air. The gas supplier is a gas cylinder with a specific gas composition such as pure nitrogen, 30% CO_2 balanced with nitrogen and so on. These gas cylinders can be purchased directly from commercial distributors or customized through the vendors. The specified gas is then flushed through the sensor bottle for an undefined period (normally five minutes) to replace the air with the desired gas. While the gas cylinder is still allowing gas to flow into the sensor bottle, the needle device is pulled out to complete the process.